

# Nucleon Structure : the Spin Content

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**Abstract.** The spin structure of the nucleon has been investigated for long years. In the light of new experimental data from HERMES, COMPASS, J-Lab, and RHIC-spin, current status of our knowledge of the spin structure is discussed. Prospects with future facilities are also described.

**Keywords:** hadron structure, spin polarization

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## WHY SPIN STRUCTURE?

Spin is one of the most important concepts in the development of modern physics. The concept appears in many different levels including very large scale phenomena such as spiral galaxies and very microscopic levels such as space-time structure described in spin networks. In particle/nuclear physics the concept is also very important, since it couples to the angular momentum conservation originated in the rotational symmetry of space. The statistical characteristic of an elementary particle is also determined from the spin.

On the other hand, the structure of the nucleon has been investigated for long years especially by using the lepton scattering. Such experiments provided the basis of the quantum chromodynamics through the discovery of the asymptotic freedom. The discovery potential of the hadron colliders would have never been so promising without a detailed knowledge on the nucleon structure. The knowledge is also very fundamental, since more than 99% of the visible universe consists of the nucleon.

Given these backgrounds, it is understandable that the phenomena called “proton spin crisis” was received with a large interest. The quark-spin contribution to the proton spin was measured to be small in lepton scattering experiment[1]. However, the nucleon already had gone through so many crises. For example, the mass of the nucleon cannot be explained from the bare quark mass. Instead most of the mass is explained in terms of chiral condensates. The second example is the momentum of the proton. When the fractional momentum,  $x$  carried by quarks was integrated over  $0 \leq x \leq 1$ , it comes to only  $\sim 50\%$  of the total momentum. The rest of the momentum is carried by the gluons. This is referred to as momentum sum rule.

Similarly there is a spin sum rule to explain the proton spin from quark spin, gluon spin and their orbital motion;

$$\frac{1}{2}^{\text{proton}} = \frac{1}{2} \Delta \Sigma + \Delta g + L_q + L_g. \quad (1)$$

Fractional quark-spin contribution  $\Delta \Sigma$  is obtained to be 0.1–0.3 from lepton scattering data combined with the  $\beta$ -decay constants of octet baryons, which is significantly

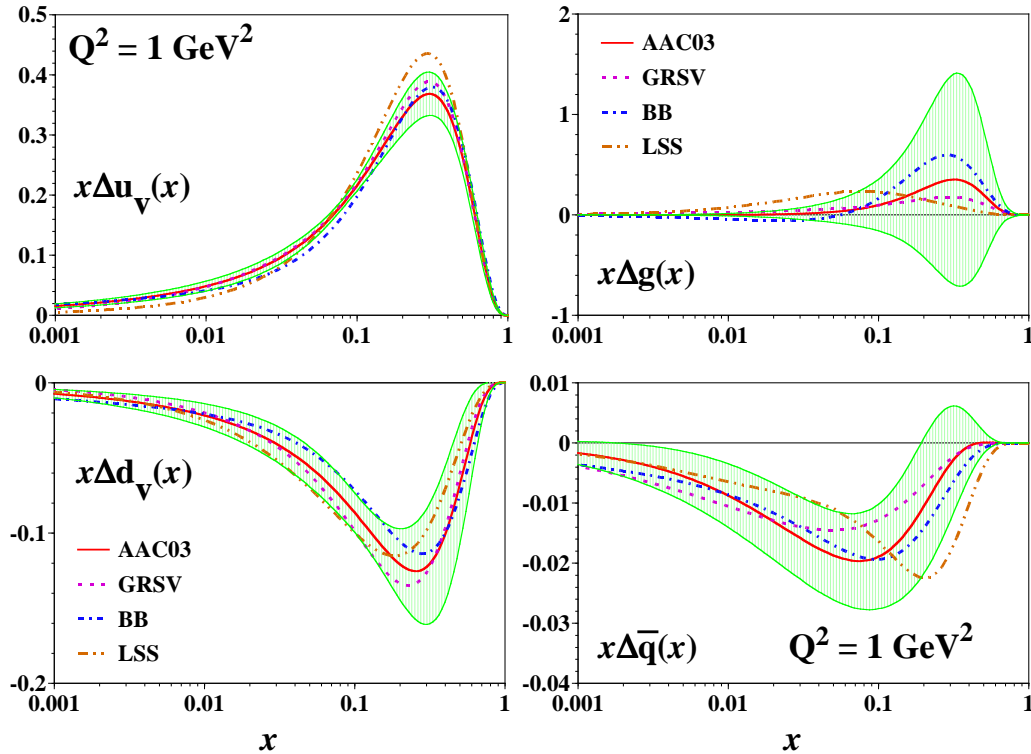
smaller than naive expectation, and called “proton spin crisis”. The gluon spin contribution  $\Delta g$  and quark and gluon orbital contributions,  $L_q$  and  $L_g$ , respectively, remain unmeasured. These components are the 1st moment of corresponding Bjorken  $x$ -dependent functions at a certain energy scale,  $\mu$  e.g.

$$\Delta g(\mu) = \int_0^1 g(x, \mu) dx \quad (2)$$

There is a theory guideline for the separation of proton spin described in the Equation, by Ji, Tang, and Hoodboy[2]:

$$\frac{1}{2}\Delta\Sigma + L_q = \frac{1}{2} \frac{3N_f}{3N_f + 16} ; \Delta g + L_g = \frac{1}{2} \frac{16}{3N_f + 16} \quad (3)$$

Each corresponds to 0.18–0.26 and 0.32–0.24, respectively depending on the number of flavors  $N_f$ , three through six. Once  $\Delta g$  is measured to a reasonable precision, then we will know roughly how the spin of the proton is distributed to each component.



**FIGURE 1.** Polarized parton distribution functions extracted from inclusive DIS data through next-to-leading order  $Q^2$  evolution.

Above spin sum rule is for the longitudinal spin structure of the proton. Triggered by the “spin crisis” and also very interesting experimental data such as unexpectedly large  $A_N$  for forward pion production[3, 4], there has been a lot of progress in understanding the transverse spin structure, too. However, due to the limited space and time, we would concentrate on the gluon polarization issues in this manuscript.

There are several good reviews[5] on this subject. Readers should refer to those reviews for more comprehensive picture.

# POLARIZED PARTON DISTRIBUTION FUNCTIONS

In Figure 1, we show the current understanding of polarized parton distributions obtained through next-to-leading order analysis of data from lepton scattering experiments[6]. The valence quark distributions,  $\Delta u_v(x)$  and  $\Delta d_v(x)$  are determined to a reasonable precision. The gluon distribution  $\Delta g(x)$  and sea quark distribution  $\Delta q_{sea}(x)$  remain to be determined better.

Uncertainties of gluon polarization will be discussed in some details later.

Sea-quark polarization is much improved by the HERMES data on semi-inclusive DIS[7]. However, majority of the global analysis group assume  $SU(3)_{\text{flavor}}$  symmetric sea due to a limited precision obtained so far. To go beyond the current picture of  $SU(3)$  symmetric sea, more flavor sensitive measurements are necessary.

## EXPERIMENTAL EFFORTS

There are many experimental efforts triggered by the “spin crisis”. Ongoing and future experiments are summarized in Table 1. Experimental data to determine the spin structure of the nucleon so far is far dominated by the lepton scattering data in fixed target. The efforts are being extended to cover various reactions including  $pp$  and  $ep$  colliders with the successful operation of the first-ever-built polarized  $pp$  collider, RHIC[8]. Future facilities will cover extended  $x$ -range, and also elastic scattering  $\nu N \rightarrow \nu N$  [9, 10] which could provide the 1st moment of polarized strange quark  $\Delta s$ .

**TABLE 1.** Current and future spin physics facilities.

Experiment	Reaction	Beam energies	Status
HERMES at DESY	$e^\pm p, d$	$E_e = 27$ GeV fixed target	to be completed in 2007
COMPASS at CERN	$\mu p, d$	$E_\mu = 160$ GeV fixed target	continuing
RHIC-Spin at BNL	$pp$	$\sqrt{s} = 200, 500$ GeV collider	continuing
J-Lab	$e^- N$	$E_e \sim 5$ GeV fixed target	continuing
eRHIC at BNL	$e^- p$	$\sqrt{s} = 100$ GeV collider	planned
12 GeV upgrade at J-Lab	$e^- N$	$E_e = 12$ GeV fixed target	planned
ELIC at J-Lab	$e^- p$	$\sqrt{s} = 20-65$ GeV collider	planned
J-PARC	$pp, pA$	$E_p = 50$ GeV fixed target	under construction
GSI-FAIR	$\bar{p}p$	$\sqrt{s} \sim 15$ GeV collider	planned
FINeSSE	$\nu N$ elastic	$E_\nu = 1$ GeV fixed target	proposed

These experimental facilities utilizes different probes to pin down the spin structure. Each probes has its advantages and disadvantages. As we are going to see below, it is important to use all probes to obtain comprehensive picture of the spin structure.

### *Electromagnetic interaction*

The classical, however, still leading probe in the study of structure is an electromagnetic interaction. A simple lepton scattering interaction is well understood and precisely calculable. There are many advantages in this reaction including the clear definition of

the kinematics which requires only the four momenta of in-coming and outgoing lepton. It is directly sensitive to an electric-charge squared, which results in two difficulties: (i) separation of quark and anti-quark contribution, and (ii) identification of gluon contribution. Gluon would come into a play only in the sub-leading contribution. This type of measurement have been done at CERN (COMPASS), DESY (HERMES), and J-Lab. Unfortunately one of the successful experiment HERMES will be terminated before next PANIC conference. Higher energy machines are planned at J-Lab (ELIC) and at BNL (eRHIC).

Drell-Yan production of lepton pairs also originates in the QED subprocess, which will be achievable at RHIC. Luminosity developments are underway by improving the accelerator every year. An experiment, PAX, at GSI, is planned to use  $\bar{p}_{\uparrow}p_{\uparrow}$  collisions to measure transversity distributions in the nucleon.

### *Strong Interaction*

Until recently the gluon contribution in the spin structure of the nucleon has been poorly known. By using the strong interaction, we can be very sensitive to the gluon contribution, since gluon-related processes are the leading contribution. Therefore, the direct measurement of the gluon polarization using the polarized  $pp$  collider, RHIC has been longed.

Jet production is one of the most promising process due to its abundance. Leading hadron can be used as a jet surrogate, too. In both cases the leading processes are  $gg$ ,  $gq$  and  $qq$  scattering and the  $gg$  and  $gq$  dominate in the lower  $p_T$  region where statistics is high. STAR experiment at RHIC presented their recent results on  $A_{LL}$  for jet production in  $pp$  collision at  $\sqrt{s} = 200$  GeV from Run-3 (2003)[11]. PHENIX experiment also reported their newly obtained  $A_{LL}$  for  $\pi^0$  production in Run-5[12], which will be discussed later in some details.

Gold plated mode for the gluon polarization measurement is still prompt photon production, which is dominated by gluon Compton process,  $gq \rightarrow \gamma q$ . In a sense, this is a half strong and a half electromagnetic, since its leading contribution starts from  $\mathcal{O}(\alpha_S \alpha_{EM})$ . Similar goes to photo-production of charmed mesons or hadron-pairs in photon-hadron interaction, which is being explored in HERMES and COMPASS. Here real/virtual photon and gluon fuse into  $q\bar{q}$  pair, thus referred to as photon-gluon fusion. Current experimental data points to constrain gluon polarization  $\Delta g/g(x)$  solely from this process.

### *Weak interaction*

However, still missing information is the flavor separation, which can be finally achievable using the weak interaction.  $W$  production in  $pp$  collisions is pure  $V - A$  process, where only left-handed quark and right-handed anti-quark can contribute and it is an ideal place to study spin structure.  $W$  couples to weak charge, which is highly correlated with the flavor. Therefore it is suitable in flavor structure studies.

Such measurement is feasible at RHIC when it reaches its highest energy  $\sqrt{s}=500$  GeV. In 2005, we have achieved  $\sqrt{s} = 410$  GeV. We plan to commission the machine at 500 GeV in 2006. Physics production at 500 GeV is expected to start in 2009.

Flavor studies are being done by using another class of lepton scattering process called semi-inclusive DIS, in which additional hadron is required in the final states to select the probed flavor. This attempt has been rather successful and reported by HERMES experiment in this meeting [7].

In near future, high intensity  $\nu$  beam will be available at J-PARC and Fermilab. There are some efforts to realize the measurement of elastic scattering  $\nu N \rightarrow \nu N$ . The measurement is useful in the determination of  $\Delta s$  [13], which is currently obtained to be negative. To determine the components appeared in Eq.1, we need to integrate the corresponding parton distributions over  $0 \leq x \leq 1$ . On the other hand, the elastic scattering will provide the integrated value as a whole in the limit of  $Q^2 = 0$  GeV<sup>2</sup>. Previous experiment at BNL[14] provided the cross section for the elastic scattering. However, the determination was rather limited due to rather high  $Q^2$ -cut ( $Q^2 \geq 0.4$  GeV<sup>2</sup>). In addition, most of the events were from the bound proton in carbon which may be subject to substantial nuclear effects. Therefore, it is desirable to have pure hydrogen target and to go to lower  $Q^2$  as much as possible. Such measurements are being studied either at Fermilab and/or J-PARC.

## GLUON POLARIZATION

There have been significant efforts to measure gluon polarization in the proton. Current constraints are summarized in Figure 2.

There are several direct measurements as summarized in Table 2. Data points are available from HERMES, SMC, and COMPASS experiments.

Phenomenologically the gluon polarization  $\Delta g/g(x)$  is determined from the scaling violation of DIS data. Two typical results [6, 15] are shown with the range of uncertainties. They are both consistent with the direct measurements and there are still room for either positive or negative gluon polarization. A theoretical prediction by Brodsky and Schmidt [16],  $\Delta g/g(x) \sim x$  is also shown in the Figure, which is consistent with the GRSV curve. This is a remarkable agreement, given these are obtained through completely different approaches.

We discuss what has been expected, and measured, and what is going to be measured in a near future below.

*Expectation.* There are two reasons (at least phenomenologically) to hope for rather large  $\Delta g$ . One reason is to fill the gap between expected value of fractional contribution of quark spin to the proton ( $\tilde{\Delta\Sigma}$ ) and the measured-extracted value ( $\Delta\Sigma$ ) through axial anomaly:

$$\Delta\Sigma = \tilde{\Delta\Sigma} - \frac{N_f \alpha_s}{2\pi} \Delta g. \quad (4)$$

Since  $\alpha_s \sim 0.5$  at  $Q^2 = 1$  GeV<sup>2</sup>,  $\Delta g$  should be  $\sim 2$  to explain the difference. Another reason to expect large  $\Delta g$  is to compensate the spin sum rule shown in Eq. 1. Since  $\Delta\Sigma$

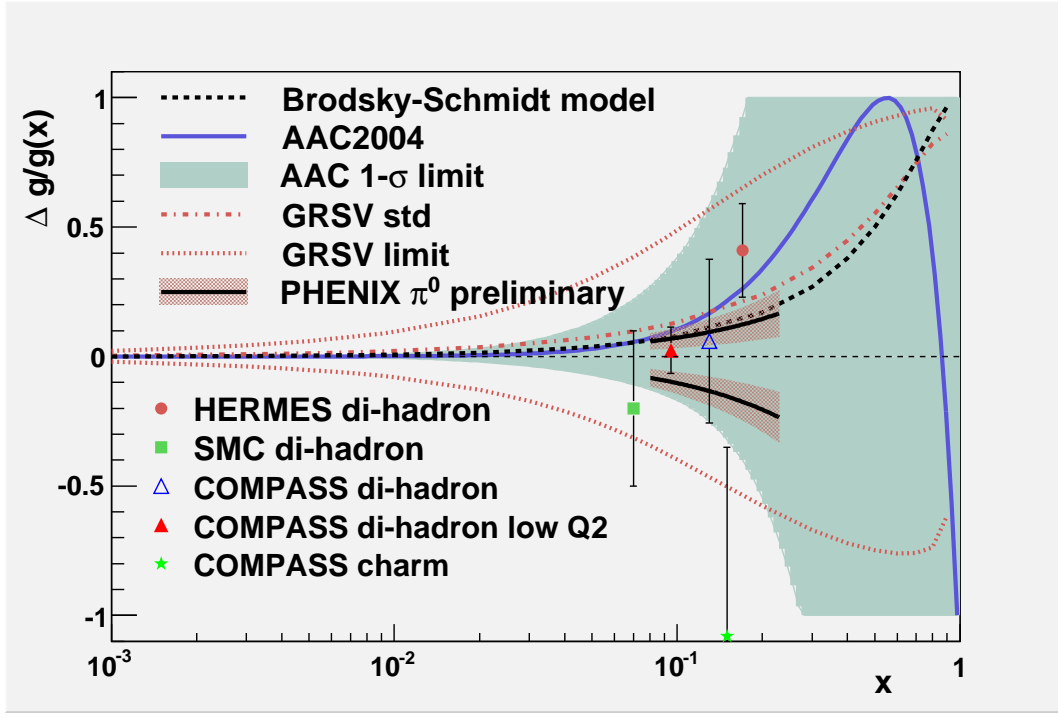


FIGURE 2. Picture to fixed height

is extracted to be 0.1-0.3,  $\Delta g \sim 0.40$  is already enough.

There are enough range of variation in the model predictions to cover these naive expectation. Bag-model calculation gives value  $\Delta g \sim -0.4$ [17]. QCD sum-rule calculation gives “upper limit”  $\Delta g \sim 2 \pm 1$ [18]. Differently from the quark-spin contribution, it seems rather hard to evaluate in numerical simulations using Lattice gauge theory[19]. There has been a substantial discussion on the gauge dependence of gluon polarization[20].

However it should be noted that the  $\Delta g$  is highly scale dependent. It is predicted that  $\alpha_s \Delta g$  should remain constant. Since  $\alpha_s$  runs as  $\ln Q^2$ ,  $\Delta g$  would run as  $1/\ln Q^2$ .  $\alpha_s(1 \text{ GeV}^2) \sim 0.5$  and  $\alpha_s(M_Z^2) \sim 0.1$ ,  $\Delta g(1 \text{ GeV}^2) = 2$  means  $\Delta g(M_Z^2) \sim 10$ . In a sense, the proton spin crisis is over-corrected! Total quark-gluon contribution will be reduced back to 0.5 especially by *negative* contribution from  $L_g$  [21]. In any case, a *naive expectation* may hold only at a certain scale and if we go to a different energy scale, we need to adapt ourselves to a deviation from natural expectation.

**Measurements.** Experimentally there have been extensive efforts to measure, or constrain at least  $\Delta g(x)$  in either lepton or hadron scattering. Direct constraints from  $pp$  collision were obtained in Fermilab E704 [22] and by HERMES [23] in '90s. Indirect constraints have been obtained through scaling violation of  $g_1^{p,n}(x)$  by many phenomenological analysis group.

As in the case of any structure function measurements, one experiment can cover only limited  $x$ -range. Obviously we are trying to answer the question of the 1st moment,

which is the integral of the structure function at  $0 \leq x \leq 1$ . Differently from quark measurement there is no direct measurements of the 1st moment in gluon polarization. Therefore it is very important to have (a) several experiments to cover reasonable range of  $x$  to extrapolate the measurements to  $x \rightarrow 0$  and  $x \rightarrow 1$  reliably, (b) reasonable measure of kinematical values  $x$  and  $Q^2$  covered by the experiments. The latter part is not trivial as was in the quark case.

A major process to measure  $\Delta g(x)$  in lepton scattering experiment is photon-gluon fusion process. Reconstruction of the parton level kinematics is not possible unless entire jet fragments are detected in the final state. Then QCD event generator is often employed to estimate the momentum fraction,  $x$  carried by initial state gluon. The technique is further extended to evaluate the background contribution such as resolved photon process.

Hadron collision is more complicated because two initial partons are involved. Even with the complete detection of the final states, ambiguity of assignment of reconstructed  $x$  to the initial state remains. In principle, QCD event generator can be used to reconstruct the parton level kinematics, to estimate the background, and to evaluate the effect of miss-assignment. Instead, so far adopted approach is to compare with the full fledged theoretical calculation taking some models on  $\Delta g(x)$  in the market. However, this approach cannot answer the important questions; namely what is the  $x$ -region measured.

Ultimately a global QCD analysis has to be done including the hadron collision data. Such efforts are underway. For an experimentalist, to obtain some idea on the gluon polarization, we made following crude approximation. The asymmetry  $A_{LL}$  can be calculated in full next-to-leading order [24]. The asymmetry is essentially a function of  $\Delta g/g(x)$ .

$$A_{LL} = \frac{Ed^3\Delta\sigma/dp^3}{Ed^3\sigma/dp^3} \quad (5)$$

The cross section is a convolution of polarized parton distributions  $\Delta f_i(x)$ , where  $i, j = g, q$  and spin-dependent cross section at parton level,  $d\Delta\sigma_{ij}/dt$ , and fragmentation function,  $D_{\pi^0/i}(z)$  integrated in appropriate phase space  $\Delta\Omega$ ;

$$\frac{Ed^3\Delta\sigma}{dp^3}(p_T) = \sum_{(i,j)=(g,q)} \int_{\Delta\Omega} \Delta f_i(x_1) \Delta f_j(x_2) \frac{d\Delta\sigma_{ij}}{dt} D_{\pi^0/i}(z) d\Omega_{ij}. \quad (6)$$

Now we are going to apply this formula to the PHENIX  $\pi^0$  measurement. Its acceptance is limited in the central rapidity, therefore the contribution is dominated by  $x_1 = x_2$  region [24]. When we apply mean-value theorem for multiple integration, there should exist an  $x$ -value,  $\xi$  to represent the integral.

$$A_{LL}(p_T) = \alpha \left( \frac{\Delta g}{g}(\xi) \right)^2 + \beta \left( \frac{\Delta g}{g}(\xi) \right) + \gamma \quad (7)$$

Assumption made here is that relevant  $x$  values for  $gg$  scattering part and  $qg$  scattering is same. We tested this method by using a couple of  $\Delta g(x)$  models, and it works with a reasonable precision ( $\sim 10\%$ ).

We performed  $\chi^2$ -minimization to obtain a constraint on  $\Delta g/g(x)$  and the results are shown in Figure 2. Encouraged by the agreement between the Brodsky-Schmidt

model and GRSV curve,  $\Delta g/g(x) \sim a \cdot x$  is employed. As expected from the quadratic dependence on  $\Delta g/g(x)$  in Eq.7, two possible solutions are obtained and shown with uncertainty band, which is significantly underestimated because of a choice of the functional form and other assumptions made in this approach.

In combining these results with the lepton scattering data shown in Figure 2, we can see some preference on positive gluon polarization, although further precision data is desirable. If we make another stretch to calculate the 1st moment with the obtained positive solution, we obtain  $\Delta g \sim 0.3$  at  $Q^2 = 1 \text{ GeV}^2$ . Even with underestimated error, the solution is still consistent with zero within  $2\text{-}\sigma$ . Obviously we need more precision before we conclude on the size of gluon spin contribution to the proton spin.

**TABLE 2.** Direct measurements of  $\Delta g$ . In E704, PHENIX, and STAR experiments,  $x$ -range and  $\langle Q^2 \rangle$  are not specified.

Experiment	subprocess	$x$ -range	$\Delta g/g(x)$	$\mu^2$	Ref.
E704 ( $\bar{p}p, pp \rightarrow \pi^0 X$ )	$gg, qg$ scat.	—	“Large” $\Delta g$ rejected		[22]
HERMES ( $\gamma p \rightarrow h^+ h^- X$ )	$\gamma g \rightarrow q\bar{q}$	0.17	$0.41 \pm 0.18 \pm 0.03$	$2.1 \text{ GeV}^2$	[23]
SMC ( $\gamma p \rightarrow h^+ h^- X$ )	$\gamma g \rightarrow q\bar{q}$	0.07	$-0.20 \pm 0.076 \pm 0.010$	$> 2.5 \text{ GeV}^2$	[25]
COMPASS ( $\gamma p \rightarrow DX$ )	$\gamma g \rightarrow c\bar{c}$	0.15	$-1.08 \pm 0.78$	—	[26]
COMPASS ( $\gamma p \rightarrow h^+ h^- X$ )					
$Q^2 < 1 \text{ GeV}^2$	$\gamma g \rightarrow q\bar{q}$	0.095	$0.024 \pm 0.089 \pm 0.057$	$3 \text{ GeV}^2$	[27]
$Q^2 > 1 \text{ GeV}^2$ *	$\gamma g \rightarrow q\bar{q}$	0.15	$0.06 \pm 0.31 \pm 0.06$	$3 \text{ GeV}^2$	[26]
PHENIX ( $pp \rightarrow \pi^0 X$ )	$gg, qg$ scat.	—	“GRSV-max” $\Delta g$ rejected		[12]
STAR ( $pp \rightarrow jet + X$ )	$gg, qg$ scat.	—	“GRSV-max” $\Delta g$ disfavored		[11]

*Prospects.* We expect COMPASS experiment will accumulate more data on the helicity distribution. The HERMES collaboration is preparing the new results on  $\Delta g/g(x)$  from hadron-pair production. The STAR experiment has shown preliminary data in this conference, and higher statistics data being analyzed from Run-5. At RHIC, more significant improvement in both luminosity and polarization is expected by new snake magnet in its injector, AGS. Within a few years, determination of  $\Delta g/g(x)$  around  $x \sim 0.1$  will be improved to a reasonable precision, so that we can conclude about the gluon spin contribution to the proton spin. Smaller  $x$  region can be constrained from  $\sqrt{s} = 500 \text{ GeV}$  run at RHIC in a few years.

In the end of this section, it would be worth mentioning the importance of the unpolarized distributions. All measurements mentioned above are sensitive to the gluon polarization,  $\Delta g/g(x)$  in certain  $x$ -ranges. To answer the question of  $\Delta g$ , we need to multiply by unpolarized gluon distribution  $g(x)$ , which is poorly determined in large- $x$  and small- $x$  region. Smaller region can be measured at future facilities such as eRHIC/ELIC, and larger- $x$  region can be measured at J-PARC. In the next decade, our knowledge on the gluon section of the proton structure will be significantly enhanced.

## SUMMARY

There has been a significant improvements in the knowledge of the spin structure of the nucleon. We reviewed the progress in the gluon sector, and showed the possible size of the gluon spin contribution, which turns out to be sufficient to fulfill the spin

sum rule, but unlikely to be large enough to explain small quark-spin contribution through axial anomaly. Further clarification is necessary before we conclude on the gluon polarization in the nucleon. Near future measurements will further explore the spin structure including the transverse structure, and we expect to have more comprehensive picture of the structure of hadrons before the next PANIC conference.

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